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Useful Pictures: Joseph Black and the Graphic Culture of Experimentation

MATTHEW DANIEL EDDY

Introduction

In the history of science Joseph Black is best known for his isolation of fixed air (carbon dioxide) in the 1750s. But in addition to his experimental research, he taught chemistry in the University of Edinburgh's Medical School for the last four decades of the eighteenth century.[1] While his students were certainly impressed with their professor's chemical expertise, they also regarded him as a skilled teacher and a gifted communicator. Crucial to his teaching was a carefully curated assemblage of diagrams and figures that depicted theoretical and practical aspects of chemical affinity. They occur in most student notebooks taken in his lectures and, though studies on Black's chemistry cite them in reference to his experimental research, they are seldom treated independently as visual objects of inquiry that were designed primarily for teaching students. Building on recent research that underscores the pedagogical and visual facets of Black's diagrams,[2] this essay further explores how Black's visualisations were relatively simple pictures to which he attached chemical meanings that were easy for his students to understand.

Throughout the four decades in which he taught at Edinburgh, Black employed simple visual structures to represent how substances were attracted to each other in compounds. During the eighteenth century most chemists held that substances were bound together by an invisible force of attraction called affinity. They did not, however, have a unit to measure the force of attraction. But, based on painstaking experimentation, they knew that most substances had a stronger or weaker attraction to other substances. Thus, in simple reactions, they could predict which substance would unite with another. This kind of attraction was called 'single elective affinity'. For more complex reactions, they used the term 'double elective affinity' to try and explain how the competing attractions of different substances resulted in the final products.

Black used two kinds of pictures to visualise various aspects of single and double attractions. First, he employed figures to depict instruments and experimental tableaux. Such figures were mimetic pictures, in that they sought to represent objects that could easily be seen by the human eye. Secondly, he used diagrams to represent scientific concepts like heat and force that could not be observed directly by the human eye. These diagrams were schematic in that they reduced unobservables to simple lines and patterns that could be easily remembered and quickly drawn. To visualise single elective affinity he used the square, or, more specifically, he used a square-shaped affinity table. For double elective affinity, he used a circlet diagram to represent a basic reaction and a chiastic diagram to represent the ratios of attraction between substances. When used together, the three diagrams – the table, the circlet and the chiasm – collectively visualised the theoretical underpinning of his chemistry and, hence, functioned as a visual system (Plate 2).

When Black's students attended his lectures, they had to learn how to use his figures and diagrams as pictures that could be read in a number of ways. This means that these pedagogical images consisted not only of a visual form, but also of a set of practices used to learn, make and understand that form. They were visualisations that students were taught to think with, things that shaped what they knew and what they thought they knew. It is this active view of an image that is used in the following sections to unpack Black's figures and diagrams, especially the notion that they were visual forms which gained meaning and value as they moved through time and space in the notes kept by professors and students. The intention is to gain deeper understanding of the role they played as learning tools and informatic devices that made chemistry easier for students to understand.

A Graphic Continuum

The most influential visualisation used to teach chemistry during the eighteenth century was the affinity table proposed by the French academician Étienne François Geoffroy in 1718. Even thought it was a 'table', its rows and columns read more like a diagram. It consisted of lists of substances and it was reproduced and modified throughout the century.[3] This kind of visualisation was used in an age when both tables and polygons were considered images. In Britain this view of representation was expressed in the works of the philosopher and physician John

Locke, whose views on the cognitive efficacy of graphic culture were taken up by Scottish intellectuals during the mid eighteenth century. Consequently, most works written by Scots on pedagogy promoted an educational psychology that advocated the use of images made from words and simple lines, thereby transforming simple schemata or even lists into crucial learning tools that also served as information management devices. This view of pedagogical pictures treated them as knowledge-making artefacts and, as such, it resonates with current research in anthropology, art history, psychology and the history of science.[4]

Many of Black's figures and diagrams were similar to those used in many early modern institutions which taught medicine and natural philosophy.[5] But unlike the three-dimensional figures of body parts and experimental apparatus depicted in reference books designed for popular consumption, pictures used for medical instruction in Scotland tended to be more schematic because they were often being used alongside the anatomical specimens and instruments that they were meant to represent. Black and his Edinburgh colleagues were heirs to the graphic techniques of this tradition.

Black's pictures existed in a temporal continuum of graphic iteration and innovation. As intimated above, some extended contemporary graphic traditions in medical chemistry and natural philosophy. Others, such as the affinity table, were adaptations of forms taken from the longstanding mnemotechnic tradition. Additionally, he changed them over time as needed throughout the course of his career. In this respect – that is, in relation to their usage – his pictures were, firstly, part of a general tradition of schematic representation and, secondly, part of the particular chronology of each chemist who used or modified them. Tracing these kinds of modifications or changes in the world of Enlightenment chemistry is generally difficult because it is a challenge to find extant sources that are appropriate.

Fortunately, Edinburgh's chemistry students left behind many notebooks. These show that the concept of using chemical visualisations like diagrams and figures had already been firmly established by William Cullen, Black's teacher and mentor.[6] They also reveal that, though the basic chiastic, circular and tabular forms of Black's diagrams remained relatively consistent over his career, he modified them in a number of ways. Additionally, his affinity table and its symbols – like most affinity tables used by Enlightenment chemistry teachers – also built on a visual tradition introduced by Geoffroy in 1718.

Black was very aware of the foregoing temporal continuum of visualisation, and commented on how the arrangement and content of his affinity table either extended or departed from graphic forms of representation used in the distant and recent past. This awareness is perhaps most clearly evinced in the sections of his lectures that explained the meaning of his chemical symbols. When the Swedish chemist Torbern Bergman definitively isolated a substance called calcareous earth during the 1770s, for instance, Black appropriated Bergman's symbol for it. In the lectures he gave over the next two decades, he took care to tell his students how and why Bergman had constructed the symbol from previously existing 'marks'.[7]

Black also redesigned some of his chemical symbols so that they could be more easily remembered by his students. Notably, he felt it was important to explain the historical context of his decision. The best example of his practice can be seen in his redesign of the symbol used for general alkalis. Black explained the change to his students in the following manner: 'For Alkalis in gen[eral] I use a Circle with a semi Circle added to one side. The Mark used in Geoffroy's Table is very diff[erent], but it is like the mark for Vitriol [in that] it is not easy to remember it, & thus is more simple and distinct.'[8]

Black's diagrams also extended local Scottish traditions of representation. His circlets extended the kind of geometric circles used in university natural philosophy textbooks, and his chiasm was a redeployment of a graphic calculation device used by Reformed schoolchildren. But his iterations of such images were not straightforward replications, and he made alterations to them throughout his career so that he could visualise new developments in chemistry. Thus, as his career progressed and he learned more about chemistry and teaching, he transformed the numeric ratios of his chiasm into algebraic equations and he inserted additional substances into his circlets.[9]

Black's figures and diagrams were more like snapshots, idealised moments that were frozen in time. In this respect they were atemporal and this meant that Black had to communicate the temporal instructions verbally. Even when students attended lectures and actively sought to connect the meaning of Black's pictures to his hands-on experimental practices, they still had to grapple with the fact that he had often done part of the experiment prior to their arrival in the classroom.[10] This means that Black's figural depictions of experimental tableaux were in many ways an attempt to mitigate this temporal conundrum (Plate 3).[11] But the important point to note here is that the number and order of steps required to conduct a successful experiment were explained in the *verbal* instructions, and not strictly in Black's *visual* depictions.

Since Black's pictures were *prima facie* atemporal depictions, it was rather difficult to discern their temporal meanings when students first encountered them. It was only when students watched Black conduct and explain his experiments in the classroom that they learned to attach elements of temporality to them. When read one way, for example, the chiasm could be interpreted to depict substances that were together at the *start* a reaction (Plate 2a). When read another way, the chiasm could be interpreted to represent the substances that were together at the *end* of the reaction. This multistable aspect of Black's pictures made them versatile, but it also meant that they were difficult to interpret without having attended his lectures or, at the very least, without having access to a very thorough set of notes that were taken in his class.[12]

The temporal complexity of Black's pictures can also be seen in the alphabetical headings that he used to label his figures. The narrative instructions that corresponded to such headings were effectively step-by-step procedures which governed the order of the actions that needed to be taken in a set of multi-stage experiments.[13] As such, the figures and their headings corresponded to lists of experimental events or episodes, all of which added up to a final product that could be explained through the affinity model. The best way to understand the temporal dimensions of Black's figures was, again, to watch him perform the experiment in person. Barring this form of multi-sensual learning, students who missed the lecture had to resort to the oral or written accounts of other students.

Attaching Time to Figures

Black made his figures visually simple so that students could easily associate them with what they had seen in lectures. His figures came in two schematic varieties. The first were small pictograms. The objects of these pictograms were usually instruments and students tended to insert them between the words or sentences in their notebooks. The second were larger, more developed drawings that some students shaded with cross-hatching or, in a few cases, watercolours.[14] Like the pictograms, the objects of these drawings were instruments; however, they also included additional objects or features that helped determine the placement of the apparatus during an experiment. As shown in Plate 2b, the greater detail of these drawings made it possible to see how instruments and supporting apparatus (like connecting tubes) were set up during the experiment. In some cases, the shading or contour lines revealed modifications or singularities to the specific instruments that Black was using in his classroom experiments.

It is clear that Black gave his students some sort of standard visual depiction of important instruments or experimental setups. The distribution of figures in this manner, either as a handout or as a poster hung at the front of the room, was practised by other members of the Edinburgh medical school. Black's mentor William Cullen, for instance, hung affinity tables at the front of his classroom.[15] Black most likely presented his figures as a poster or as a handout, because the same ones appear in different sets of notes and many student drawings feature alphabetical or numerical headings that, though clearly relevant to the experiment under consideration, are not verbally explained in the notes. This strongly suggests that students simply copied the figures but then did not have time to record the meaning of the headings. It also suggests that graphic simplicity facilitated their preservation.

The use of schematic figures in this manner points to a fundamental interpretive question that is relevant to Black and most of the Enlightenment teachers who used graphic techniques to represent natural knowledge: how was the design of the figure influenced by its intended use? In Black's case, the intended users were the hundreds of medical students who attended his chemistry lectures during his tenure at Edinburgh. This means that, rather than being the 'graphic gropings' found in many laboratory notebooks, they were carefully designed to be simple visualisations that could be easily drawn and remembered.[16]

When it came to understanding the affinity concept, Black's figures also had a number of conceptual advantages. At one level they connected theory with practice because they helped to illustrate what a student could do materially in a lab with the affinity concept as represented by his chiastic and circlet diagrams, and by his affinity table. At another level they functioned as information management tools, serving as mnemonic encapsulations that helped students make sense of the step-by-step experimental instructions given during the lectures.[17] The figures also allowed students more easily to associate the invisible attractions of substances with the visible properties evinced through observation and experimentation. The main way that Black facilitated this act of association was by allowing his students to experience the smells, bangs and colours of chemical reactions.[18] While students preserved these sensations verbally in their notes and imaginatively in their minds, Black's figures of instruments such as Florence flasks, tubes, furnaces and the like functioned as schematic memory aids for what they had seen, heard and smelt.[19] In this sense, his figures were a visual reminder of chemical attractions that his students had already experienced for themselves.

It was difficult for students to interpret Black's figures without the aid of marks or symbols associated with the passage of time.[20] The experiment depicted in Plate 2c, for example, would be hard to discern were it not for the alphabetical headings that corresponded to the verbal experimental instructions written in the student's notes. Likewise, the figures were usually presented either partially or totally in one dimension, thereby removing unnecessary spatial distractions. The vessel on the right side of Plate 3, for instance, is a good illustration of this kind of schematic flatness. The figure, which is taken from a copied set of notes that Black had transcribed from his own lecture notes, is a particularly good specimen. Many student copies are even less detailed. The necessity of attending lectures to take notes that explained the figures dovetailed with an important pedagogical principle of deictic learning: the material act of inscribing further engrained the chemical products and processes that Black attached to his figures.

At the simplest level, the figures encapsulated various intervals of time that elapsed in chemical reactions. Some experiments – those with acids, for example – happened quickly, sometimes in seconds. Others, such as distillation and crystallisation, could take longer periods of time – sometimes days, or even weeks.[21] To overcome these temporal limitations, Black used substances that had been prepared in advance and summarised the steps through which the final products had originally been obtained. Regardless of how long his experimental demonstration took to prepare outside the classroom, or to perform in front of students, the figures represented chemical processes at a glance as frozen points in time.

Like so many chemical visualisations of the Enlightenment, Black's figures erased the time of all the failed experiments that had contributed to the isolation of the substances which they often featured.[22] Even though his figures were largely atemporal when not viewed in tandem with a set of lecture notes, it took a good amount of time for his students to learn how to use them. A case in point can be seen in the rough notes taken by Charles Blagden in Black's 1766 lectures.[23] Blagden would go on to be the Secretary of the Royal Society of London and one of Black's most influential students. The first time that Blagden encountered Black's circlet diagrams, however, he struggled to reproduce them in his notebook. In the end he learned to use them by shaping them as squares – an act that took some time to work out and then to copy into his notes (Plate 4).[24]

The general point to take from Blagden's unfinished circlets, or even from the many complete versions that appear in other student notebooks, is that, when the figures are treated as information management devices, it can be seen that they require an assemblage of skills and routines to use them and to make sense of them. In addition to their basic geometric structure, students had to learn, for example, the meaning of the chemical symbols and how to follow the flow of information. As Blagden's case illustrates, since there were no printed versions of the diagrams, students also had to learn how to draw them in their notebooks.

Designing Space in a Table

As evinced in the tables of Black's contemporaries, most notably in the lectures of Gabriel François Venel in France and Richard Watson in England, the traditional alignment used to organise affinity tables was a vertical column of substances listed from top to bottom (Plate 5).[25] The symbol of the main substance was placed at the top and the substances attracted to it were listed below it. The order of the list corresponded to the strength of the attraction, with the strongest at the top and the weakest at the bottom.

Black turned the traditional affinity table format on its side, transforming the columns into rows and vice versa. His table, therefore, was based on rows that were read from left to right. The main substances ran down the left side and their affinities ran horizontally, thereby positioning the strongest attractions on the left and the weakest on the right (Plate 2c). Such a structure facilitated the general left-to-right reading pattern present in sentences and the dichotomous chemical tables used by Black and other contemporary chemists in the Scottish university system and elsewhere.[26] While Black's table was unique in several ways, the notion of using rows to order substances was already known in Scotland during the mid eighteenth century. A similar alignment occurs, for example, in the affinity table of William Lewis's 1753 *Dispensatory* (Plate 6).[27] Black cites it in his 1760s lectures, and Lewis's graphic layout probably influenced his decision to make a table that read from left to right.[28]

The internal organisation of most affinity tables was based on groupings of substances that shared some sort of similarity. Geoffroy initiated this tradition by grouping salts (acids and alkalis) on the left side and metals on the right side, with water being added as a final column. Yet the meaning of his grouping, which was iterated by many mid to late eighteenth-century teachers (such as Venel), would not have been immediately apparent to students, especially since at first glance it might have seemed to them that Geoffroy had misplaced some substances. For example, it is likely that a new chemistry student would struggle to intuitively understand why Geoffroy placed *soufre mineral*, an inflammable substance, in the metallic grouping. Geoffroy's table also contained other potential classificatory confusions. The placement of the substances of course made sense when explained in lectures, but the disconnection between the conceptual order and the visual order remained a graphic problem that needed to be solved.[29]

Like Geoffroy and Venel, Black's table began with salts (acids and alkalis) and moved on to metals (Plate 2c). Since Black had turned the table on its side, the former occurred at the top and the latter appeared in the middle. Next came 'mild substances', and then a last group of substances formed by special heating factors. The order of Black's table shows that he followed the general practice of keeping salts and metals together in groups. But the crucial difference that distinguished his table from others was that it featured two graphic innovations that effectively eliminated the conceptual and visual disconnections outlined above.

First, Black broke with the practice of using a singular grid to house all the substances. Instead, he made each grouping a separate block of information. The end result was that each grouping became a visually distinct unit of information that students called a 'divisio' or 'part' in their notes. Second, Black included headings that explained the relationship between the substances contained in each block. For instance, above the first grouping, he explained its contents with the following head: 'Containing ye Relation of Alkalis and Alkaline substances to Acids &

Substances of an Acid Nature' (Plate 2c).[30] The use of such headings was a crucial pedagogical innovation because it clearly laid out the organising principle that he had used to group the affinity reactions in his table, thereby making it easier to use and understand.

Black's students could use and replicate his table in several ways. When all the groupings were viewed as one visual structure (a module, so to speak), it offered a systematic overview of the single elective attractions that played a central role in late eighteenth-century chemical experimentation conducted in medical, industrial and academic settings. When one 'part' (or 'division'), which was really a 'microtable', was read on its own, it offered a succinct overview of how affinity operated in relation to an analogous set of substances reacting in a similar way to create different compounds. Most students attempted to keep the microtables together on the same page. Paul Panton's table in Plate 2b is a good example of this practice. Other students – Thomas Cochrane, for instance – copied the microtables onto separate pieces of paper, thereby isolating one form of attraction in a way that made it easy to read and remember.[31]

Black's use of separate headings for each microtable appealed to students as well, especially when it came to the personalised nature of note-taking. Instead of copying the headings in his table verbatim, students sometimes customised the wording so that it suited their learning needs or so that it could fit into the layouts of their notebooks. This can be seen by comparing the wording of the headings used by Cochrane and Blagden during the 1760s for the second microtable. Even though the contents of both tables was the same, the headings were slightly different. Cochrane's heading reads: 'The diff[erent] Attractions of Alkalis for Acids'; while Blagden's heading reads: 'Attractions of Acid substances for [general alkali symbol] and & [metallic substance symbol]'.[32] Additionally, whereas Cochrane's heading used no chemical symbols, Blagden's heading, as intimated inside the brackets inserted into the foregoing quotation, used the chemical symbols for general alkalis and metallic substances, eliminating the need for him to write out their names.

The simplification offered by microtables and their associated headings was that they structured the page in ways that saved students from having to trawl through all the columns of the rapidly expanding affinity tables being made from the 1760s forward. Black's segmentation of the affinity table into microtables effectively created detachable visual units that could be inscribed as needed in different parts of a student's notebook, or which could be copied onto a piece of loose-leaf paper and then used alongside a specific section of the notes. This aspect of the microtables had an added advantage in that it allowed Black to visually refocus his students' attention on a set of related reactions. This advantage made it easier for students to copy the visualisation into the specific section of their notes that addressed the relevant reactions. In other words, Black's detachable microtables offered a friendlier visual format to students, mainly because they were easier to use.

Black was able to keep his microtables relatively compact because he limited the number of substances that appeared on them. Here we can see him acting as a thoughtful teacher who conscientiously mediated chemical information so that his students would not feel overwhelmed with the flood of new substances that were being discovered during the second half of the eighteenth century. Some professors tried to keep pace with these discoveries by adding many new columns to their affinity tables.[33] For instance, William Cullen's table had 31 columns, and Torbern Bergman offered up to 59 columns in his many publications.[34] Yet, despite this explosion in substances, Black continued to offer his students a segmented table of around 20 'columns' (which were actually rows, because he had turned them on their side) throughout his career.[35] He did this because he recognised the pedagogical value of using a limited amount of information to unpack complex chemical reactions.

Conclusion

This essay has shown that Black's visualisations were useful learning tools that emerged out of his teaching and research interests. In this sense they were objects that, at the most fundamental level, were designed to be used over and over again and, consequently, they gained meaning through usage. Indeed, they were simple images which he modified so that they could be used in the classroom. Since their simplicity did not visually distract his students, his figures and diagrams functioned as pictures to which he could easily attach various affinity concepts, particularly those that involved the passage of time. Yet, as we've seen, this simplicity was not accidental. It was, in fact, designed.

Black's graphic innovations made his lectures more visually accessible to his students – that is to say, to users who knew relatively little about chemistry. This motivation was probably linked in part to the fact that the number of students who took his course determined his salary. In this respect it literally paid to design teaching aids that reduced complicated topics to simple pictures. Like any informatic tool, the more one used Black's visualisations, the quicker and more helpful they became. This aspect of 'practice makes perfect' reveals an important relationship between pedagogy and what might be called 'informatic time'. The time it took to access the information in Black's visualisations depended on how much time a student had spent copying it into his notes, using it in the classroom and rereading his notes in the privacy of his study. In short, the less experience that a student had with these skills, the longer it took to use and understand the visualisations.

Black used his subtle graphic innovations to reduce complicated chemical theories down to a form of representation that could be understood by students who knew relatively little about chemistry. Key to this understanding was the fact that they could inscribe the visualisation easily and quickly into their notebooks. Likewise, Black did his best to mitigate the visual complexity of a complete affinity table by breaking it up into simple sections that students could easily remember and replicate. These graphic innovations reveal that the acquisition of scientific knowledge in Black's classroom was intimately tied to how it was visualised.

Notes and References

1 For Black's career and the practices of chemical teaching in Edinburgh during the Enlightenment, see Donovan, Arthur L., *Philosophical Chemistry in the Scottish Enlightenment: The Doctrines and Discoveries of William Cullen and Joseph Black* (Edinburgh: Edinburgh University Press, 1975); Eddy, Matthew Daniel, *The Language of Mineralogy: John Walker, Chemistry and the Edinburgh Medical School, 1750–1800* (Aldershot: Ashgate, 2008).

2 Eddy, Matthew Daniel, 'How to See a Diagram: A Visual Anthropology of Chemical Affinity', *Osiris* 26 (2014), pp. 178–96.

3 Eddy, Matthew Daniel, 'Elements, Principles and the Narrative of Affinity', *Foundations of Chemistry* 6 (2004), pp. 161–75.

4 Several aspects of this system are treated in Eddy, Matthew Daniel, 'The Shape of Knowledge: Children and the Visual Culture of Literacy and Numeracy', *Science in Context* 26 (2013), pp. 215–45.

5 An insightful treatment of the visual epistemology that influenced the use of early modern pedagogical diagrams is given in Kusukawa, Sachiko, *Picturing the Book of Nature: Image, Text, and Argument in Sixteenth-Century Human Anatomy and Medical Botany* (Chicago, IL: University of Chicago Press, 2012). See especially ch. 9.

6 Tables can be found most in notes taken in Cullen's lectures. For his figures, particularly clear renditions of the mining and furnace diagrams that he

used occur in Cullen, William, *Chemical Lectures* (1760), Anonymous (Note-taker), Bound MS, Wellcome Library, London, MS 1918, ff.126–7, 144–5, 146–7. Examples of the 'lever' diagrams he used to depict chemical reactions are featured in Cullen, William, *Adversaria Chymiæ ex prolectionibus Dr. Gulielm Cullen* (1762), Anonymous (Note-taker), Bound MS, Wellcome Library, London, MS.MSL.49, ff.44–5. For the pedagogical uses of affinity tables in Britain and France see, respectively, Taylor, Georgette N.L., *Variations on a Theme: Patterns of Congruence and Divergence among Eighteenth-Century Chemical Affinity Theories* (PhD thesis, University College London, 2006), and Lehman, Christine, 'Innovation in Chemistry Courses in France in the Mid-Eighteenth Century: Experiments and Affinities', *Ambix* 57 (2010), pp. 3–26.

7 The reception of Bergman's discovery of ponderous earth in Scotland is addressed in Eddy, *Language of Mineralogy*, pp. 137–44.

8 Black, Joseph, *A Course of Lectures on the Theory and Practice of Chemistry*, vol. 2 (1782), Anonymous (transcriber), Bound MS, Royal Society of London, MS/147/2.

9 The pedagogical origins of Black's chiasm and his modification of his chiastic and circlet diagrams are explained in Eddy, 'How to See a Diagram'.

10 Aside from the hundreds of experiments recounted every year in Black's course, other good examples of the step-by-step material manipulations that Black gave his students orally can be seen in the printed 'handouts' that he made for his students as early as the 1760s. See Black, Joseph, *The Preparations of Antimony* (n.d.) and *The Preparation of Mercury Antimony* (n.d.), in Black MS (1766–7), tucked inside vol. 7. Both antimony and mercury were important ingredients for drugs and his students would have valued having copies of how to prepare them.

11 Black, *A Course of Lectures*, lecture 61.

12 Indeed, this pictorial conundrum not only affected how Black's students and contemporaries read notes taken in his lectures, it also affects modern historians who must grapple with the fact that they often cannot see time or space in the diagrams unless they consult the lecture notes written by Black or his students.

13 Experimental or observational procedures played a central role in the graphic management of information in early modern settings. As convincingly argued by Omar W. Nasim, it is difficult to grasp the centrality of these routines without paying very close attention to scribal iterations that take place over time in scientific notebooks. Nasim, Omar W., *Observing by Hand: Sketching the Nebulae in the Nineteenth Century* (Chicago, IL: University of Chicago Press, 2013). See especially his comments in the introduction on procedures.

14 The largest number of watercolour depictions of apparatus that I have encountered appear throughout Black, Joseph, *Lectures on Chemistry*, 6 vols (1778), Paul Panton [note-taker], Bound MS, Chemical Heritage

Foundation, Philadelphia, QD14 .B533 1828. It is unclear whether these depictions were made by Panton, or whether he commissioned an artist to make them.

15 Taylor, Georgette, 'Pedagogical Progeniture or Tactical Translation? George Fordyce's Additions and Modifications to William Cullen's Philosophical Chemistry – Part II', *Ambix* 61 (2014), p. 262.

16 The term 'graphic gropings' is used *in situ* to represent laboratory work in Kemp, Martin, *Visualizations: The Nature Book of Art and Science* (London: University of California Press, 2000), pp. 72–3.

17 Black, *A Course of Lectures*, lecture 61.

18 The importance of avisual forms of evidence in early modern chemistry is underscored in Roberts, Lissa, 'The Death of the Sensual Chemist: The New Chemistry and the Transformation of Sensuous Technology', in David Howes (ed.), *Empire of the Senses: The Sensual Cultural Reader* (Oxford: Berg, 2005), pp. 106–27.

19 A number of Black's instruments are still extant. See Anderson, R.G.W., *The Playfair Collection and the Teaching of Chemistry at the University of Edinburgh 1713–1858* (Edinburgh: The Royal Scottish Museum, 1978). The instrumental context for gravimetric analysis in early modern Scotland is given throughout Connor, R.D., A.D.C. Simpson and A.D. Morrison-Low, *Weights and Measures in Scotland: A European Perspective* (Edinburgh: National Museums of Scotland, 2004).

20 Drawings of instrument pictograms occur regularly in student notebooks taken throughout Black's tenure. For representative examples from different decades see: Black MS (1766–7/1966), pp. xviii, 16, 17,21, 72, 74, 108; Black, Joseph, *Notes from Black's Chymistry* (c.1796), Bound MS, Alexander Monro *Tertius* [note-taker], University of Otago Special Collections, f. 25.

21 Black also summarised collections of related experiments conducted over a considerable period of time outside the classroom. His discussion of what might be seen as a theory of lime takes this approach. In a lecture or two, he summarised a number of experiments that would have taken days to perform outside the classroom. Black, Joseph, *Notes from Dr. Black's Lectures on Chemistry 1767/8*, Thomas Cochrane [note-taker], ed. Douglas McKie (Cheshire: Imperial Chemical Industries, 1966), pp. 68–71.

22 Omitting the visual or verbal representation of experiments or calculations that had contributed to the establishment of a scientific proposition, corollary or principle was a crucial early modern information management technique. Isaac Newton, whose methods served as a guide for most natural philosophers, omitted calculations and experiments 'for brevity's sake' in the later editions of his *Principia*. The mathematical context of these omissions is addressed in Smeenk, Chris and Eric Schliesser, 'Newton's *Principia*', in Jed Z. Buchwald and Robert Fox (eds), *The Oxford Handbook of the History of Physics* (Oxford: Oxford University Press, 2013), pp. 109–65; see especially pp. 151–2.

23 Black, Joseph, *Notes of Dr Black's Lectures, 9 Volumes* (1766–7), Charles Blagden [note-taker], Wellcome Library, London, Bound MS 1219–1227.

24 Blagden's unfinished circles occur in Black MS (1766–7), Notebook 9, f. 634 recto. His square revisualisations occur on f. 634 verso.

25 Watson, Richard, *A Plan of a Course of Chemical Lectures* (Cambridge: Archdeacon, 1771). Venel, Gabriel-François, *Cours de Chimie*, ed. Christine Lehman (Dijon: Editions Universitaires de Dijon, 2010). Many examples of eighteenth-century affinity tables occur throughout Duncan, Alistair, *Laws and Order in Eighteenth-Century Chemistry* (Oxford, 1996).

26 Dichotomous tables are also called 'branching tables' in the historical literature. They occur throughout Cullen, Bound MS (1760); see specially ff.102–3 and 152–3. For Black's dichotomous tables, see the three loose-leaf sheets (recto and verso) of dichotomies in Black, Bound MS (1778), vol. 2. As evinced in the work of Georg Wolffgang Wedel's influential *Theoremata Medica* (Jenae: Johannis Bielckii, 1677), dichotomous tables were common in medical chemistry since at least the seventeenth century. For other examples contemporary to Black's teaching, see Dossie, Robert, *Institutes of Experimental Chemistry*, vol. 1 (London, 1759), p. 275; Watson, *A Plan of a Course of Chemical Lectures*.

27 'A TABLE of the Relations or Affinities Observed between Different SUBSTANCES', in Lewis, William, *The New Dispensatory* (London: Nourse, 1753), p. 11. There seems to have been another printing of this book, because the table in the 1753 Nourse edition of *The New Dispensatory* housed in the Bodleian Library, Oxford University occurs on page xi. Copies of both editions are housed on the Eighteenth-Century Collections Online Database.

28 Black MS (1766–7/1966), p. 119. Black directed his students' attention to Lewis's mercury preparations.

29 The logic of Geoffroy's arrangement is discussed in Klein, Ursula and Wolfgang Lefèvre, *Materials in Eighteenth-century Science: A Historical Ontology* (Cambridge, MA: MIT Press, 2007), pp. 147–50.

30 It should be noted here that Panton's affinity table lacks a heading for the fourth grouping on the table. Such a heading, however, is present in most other sets of student notes.

31 Thomas Cochrane's microtables are reproduced in Black MS (1766–7/1966), pp. 161–5.

32 Charles Blagden's version of the affinity table is recorded in Black MS (1766–7), vol. 9., f. 631r.

33 Duncan, *Laws and Order*, pp. 112–14, 132–6.

34 Cullen, William, *Lectures on Chemistry delivered at Edinburgh University, 3 Volumes* (1765), William Falconer [note-taker], Bound MS, Wellcome Library, London, MSS 1919–1921. Cullen's 31-column table occurs in vol. 2, MS 1921. Bergman's tables are discussed in Duncan, *Laws and Order*. See also the 50-column table, 'Single elective attractions: in the Moist Way; in

the Dry Way', in Bergman, Torbern Olaf, *A Dissertation on Elective Attractions* (London: J. Murray, 1785).

35 In his paper on the discovery of carbon dioxide (which he called 'fixed air'), Black argued for the expansion of Geoffroy's affinity table. Black, Joseph, 'Experiments upon Magnesia Alba, Quicklime, and Some Other Alcaline Substances', *Essays and Observation, Physical and Literary*, 2 (1756), pp. 157–225. See especially pp. 224–5. Other late eighteenth-century chemistry teachers also used a simple affinity table for university chemistry lectures. See, for example, the table in Watson, Richard, *A Plan of a Course of Chemical Lectures, by R. Watson, D.D.F.R.S. and Regius Professor of Divinity in the University of Cambridge* (Cambridge: Archdeacon, 1771).

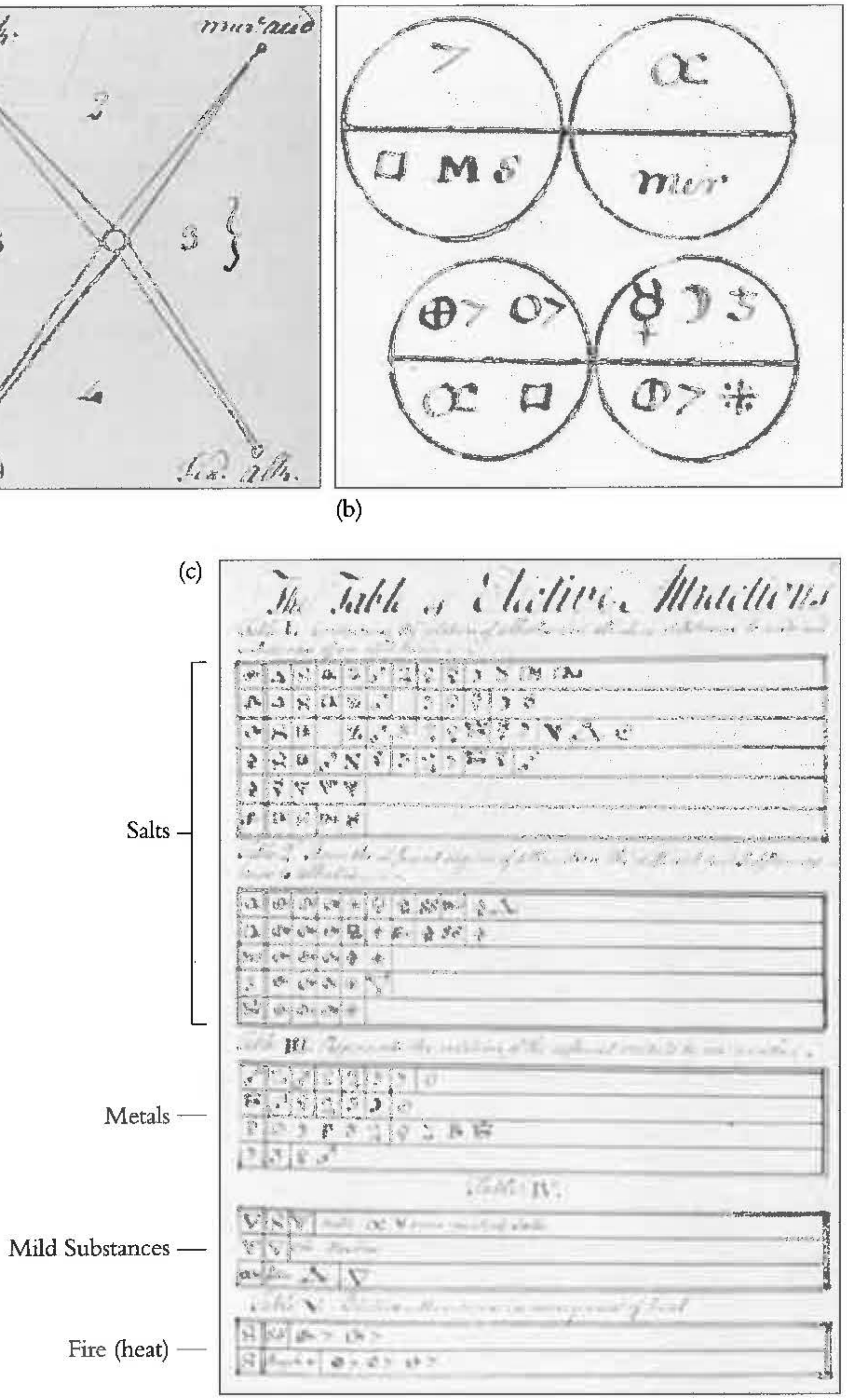


Plate 2. Joseph Black's three main visualisations of affinity were (a) chiasm, (b) circlets, (c) a square affinity table. From Paul Panton's notes taken at Joseph Black's lectures, 1778, Chemical Heritage Foundation MS QD14.B533 1778 (chiasm: vol. 3, f. 107; circlet: vol. 6, f. 67; table: vol. 6, f. 17).

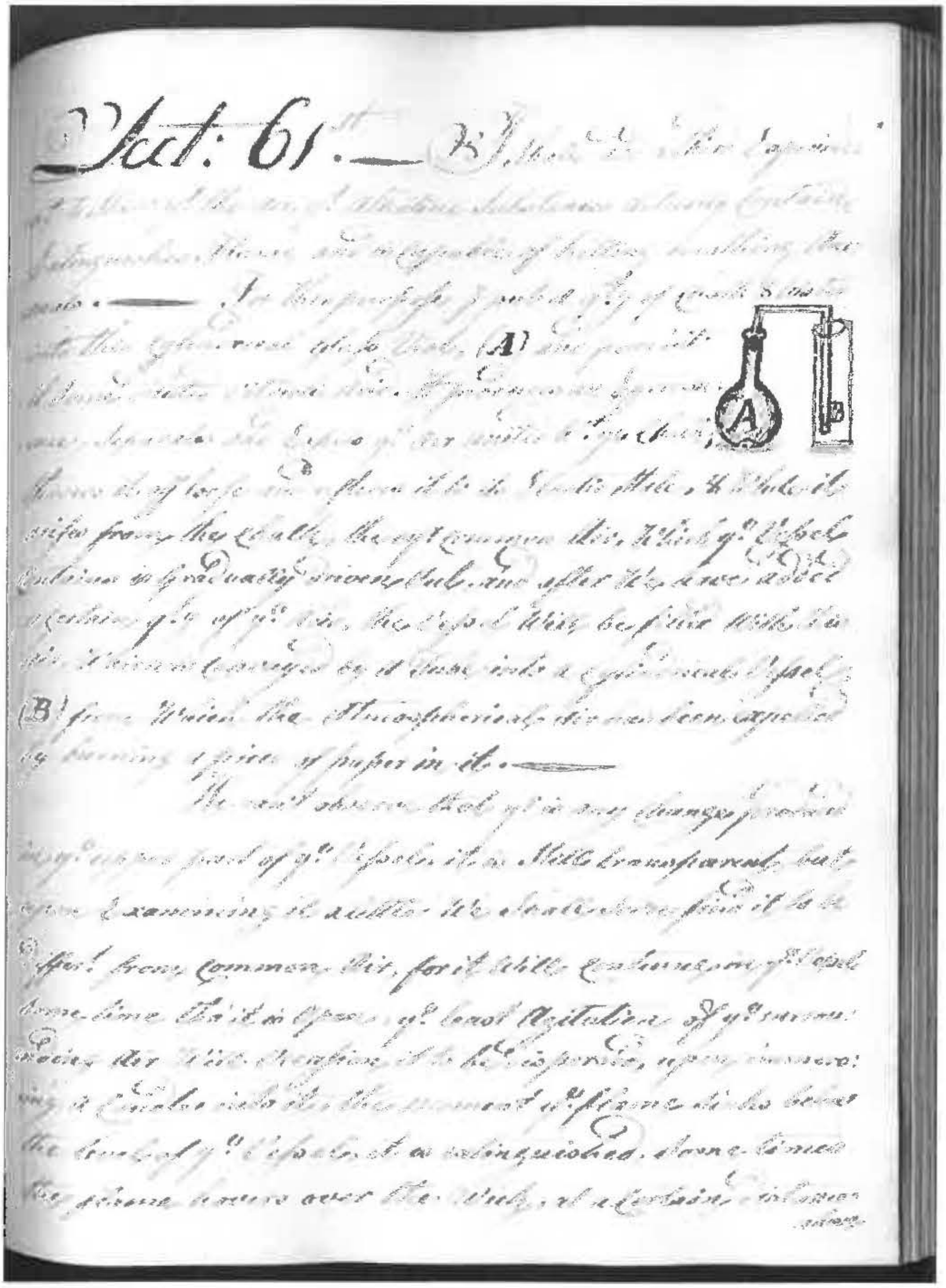
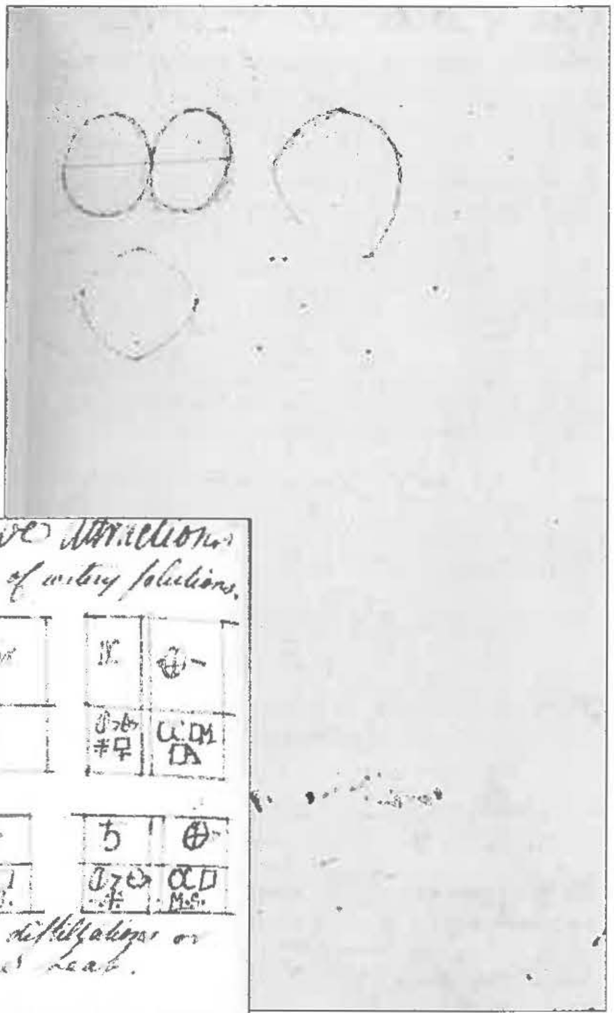
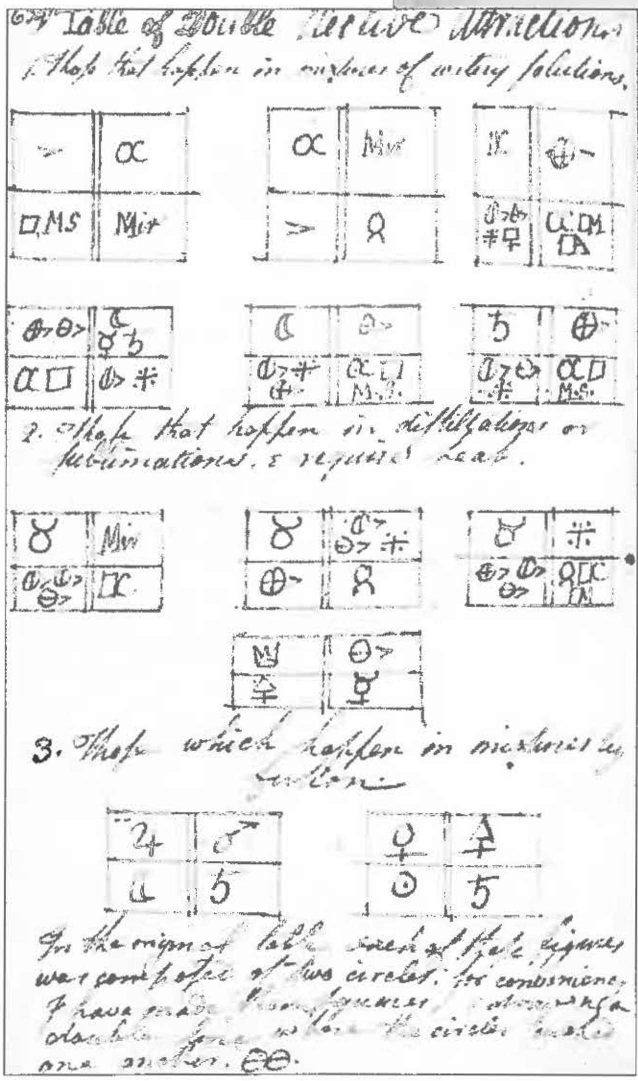


Plate 3. Experimental apparatus depicted alongside a set of instructions in Joseph Black's transcribed 1782 lecture notes. Royal Society of London.

Plate 4.
Right: Charles Blagden's unsuccessful attempt to inscribe Black's affinity circlets into his student notebook.

Below: Blagden's reconfiguration of Black's circlets into squares.
Wellcome Library, London.





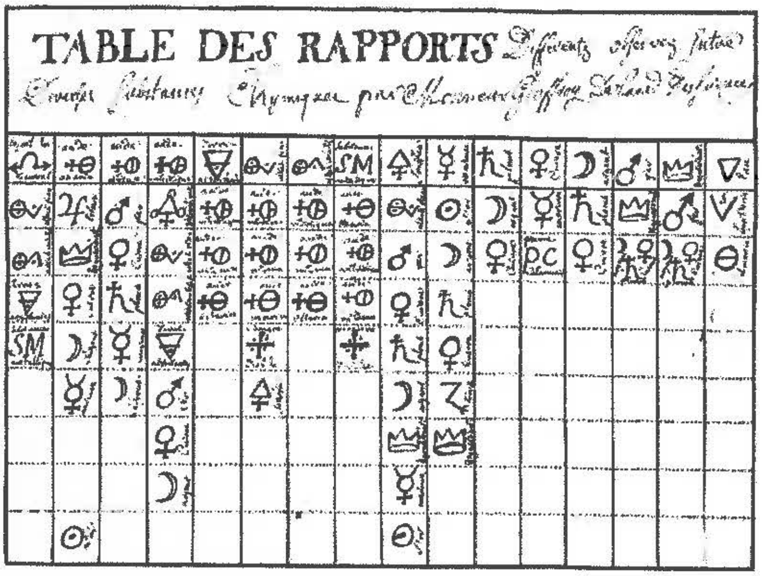
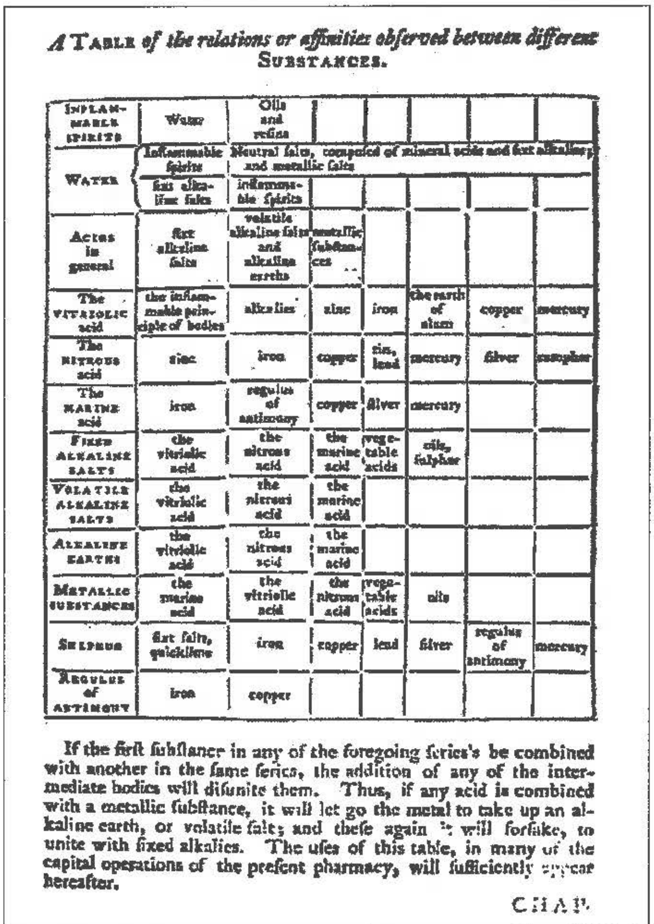


Plate 5. *Above*: Venel, Gabriel François (1723–1775), 'Table des Rapports', *Cours de Chymie*, Wellcome Library, London.

Plate 6. *Right*: Affinity table in Lewis, William, *The New Dispensatory* (London: Nourse, 1753), p. 11.



A TABLE *of the relations or affinities observed between different* SUBSTANCES.

INFLAMMABLE SPIRITS	Water	Oils and resins					
WATER	Inflammable spirits	Neutral salts, composed of mineral acids and fixt alkalies, and metallic salts					
	fixt alkaline salts	inflammable spirits					
ACIDS in general	fixt alkaline salts	volatile alkaline salts and alkaline earths	metallic substances				
The VITRIOLIC acid	the inflammable principle of bodies	alkalies	zinc	iron	the earth of alum	copper	mercury
The NITROUS acid	zinc	iron	copper	tin, lead	mercury	silver	camphor
The MARINE acid	iron	regulus of antimony	copper	silver	mercury		
FIXED ALKALINE SALTS	the vitriolic acid	the nitrous acid	the marine acid	vegetable acids	oils, sulphur		
VOLATILE ALKALINE SALTS	the vitriolic acid	the nitrous acid	the marine acid				
ALKALINE EARTHS	the vitriolic acid	the nitrous acid	the marine acid				
METALLIC SUBSTANCES	the marine acid	the vitriolic acid	the nitrous acid	vegetable acids	oils		
SULPHUR	fixt salts, quicklime	iron	copper	lead	silver	regulus of antimony	mercury
REGULUS of ANTIMONY	iron	copper					

If the first fubftance in any of the foregoing feries's be combined with another in the fame feries, the addition of any of the intermediate bodies will difunite them. Thus, if any acid is combined with a metallic fubftance, it will let go the metal to take up an alkaline earth, or volatile falt; and thefe again it will forfake, to unite with fixed alkalies. The ufes of this table, in many of the capital operations of the prefent pharmacy, will fufficiently appear hereafter.

CHAP.